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Peroxisome Proliferator-Activated Receptor- γ Regulates the Expression of Alveolar Macrophage Colony-Stimulating Factor

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Abstract

Macrophage CSF (M-CSF) regulates monocyte differentiation, activation, and foam cell formation. We have observed that it is elevated in human pulmonary alveolar proteinosis (PAP) and in the GM-CSF knockout mouse, a murine model for PAP. A potential regulator of M-CSF, peroxisome proliferator-activated receptor- γ (PPAR γ), is severely deficient in both human PAP and the GM-CSF knockout mouse. To investigate the role of PPAR γ in alveolar macrophage homeostasis, we generated myeloid-specific PPAR γ knockout mice using the Lys-Cre method to knock out the floxed PPAR γ gene. Similar to the GM-CSF-deficient mouse, absence of alveolar macrophage PPAR γ resulted in development of lung pathology resembling PAP in 16-wk-old mice, along with excess M-CSF gene expression and secretion. In ex vivo wild-type alveolar macrophages, we observed that M-CSF itself is capable of inducing foam cell formation similar to that seen in PAP. Overexpression of PPAR γ prevented LPS-stimulated M-CSF production in RAW 264.7 cells, an effect that was abrogated by a specific PPAR γ antagonist, GW9662. Use of proteasome inhibitor, MG-132 or a PPAR γ agonist, pioglitazone, prevented LPS-mediated M-CSF induction. Using chromatin immunoprecipitation, we found that PPAR γ is capable of regulating M-CSF through transrepression of NF- κ B binding at the promoter. Gel-shift assay experiments confirmed that pioglitazone is capable of blocking NF- κ B binding. Taken together, these data suggest that M-CSF is an important mediator of alveolar macrophage homeostasis, and that transcriptional control of M-CSF production is regulated by NF- κ B and PPAR γ .

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Peroxisome proliferator-activated receptor- γ (PPAR γ)² is a member of the ligand-activated nuclear hormone receptor family that can function as a transcription factor (1). PPARs have been reported in the regulation of genes involved in lipid and glucose metabolism as well as inflammation (2,3). Although weakly expressed in monocytes, PPAR γ is up-regulated during differentiation into macrophages and is predominantly nuclear in location (4). Our studies are the first to describe the constitutive expression of PPAR γ in healthy human alveolar macrophages and the striking deficiency of PPAR γ in pulmonary alveolar proteinosis (PAP).

Alveolar proteinosis is an autoimmune disease in which neutralizing autoantibodies to GM-CSF result in a deficiency of bioactive GM-CSF in the lung (5). Intraalveolar accumulation of periodic acid-Schiff (PAS)-positive lipoproteinaceous material inhibits gas exchange in the lungs of patients with PAP (6). The deficiency of PPAR γ can be reversed in vitro by GM-CSF and therapeutically in disease by treating with exogenous GM-CSF (7). Alveolar macrophages obtained from the GM-CSF knockout (KO) mouse, the animal model of PAP, are also deficient in PPAR γ .

Monocytes recruited into the lungs are thought to mature into alveolar macrophages in a process dependent upon GM-CSF (8,9). GM-CSF and macrophage CSF (M-CSF) are CSFs associated with the regulation of myeloid differentiation (10–13). The lack of GM-CSF has been thought to be a trigger for increased production of M-CSF as a compensatory mechanism, although this issue remains incompletely defined (14,15). In support of this, we and others have observed that both human PAP and the GM-CSF KO mice overproduce M-CSF (5,16). Furthermore, therapeutic administration of biologically active GM-CSF restores PPAR γ levels and decreases M-CSF in human PAP (17,18).

GM-CSF has been implicated in the classical activation of macrophages resulting in the up-regulation of MHC class II molecules and CD86, whereas M-CSF has been associated with alternative macrophage activation (19). Alternative macrophage activation by M-CSF has been linked to the induction of IL-10 and matrix metalloproteinases (19–21), both of which are elevated in PAP (17,22). M-CSF has also been associated with enhanced foam cell formation in vitro (23–25). These observations suggest that M-CSF may play a role in the accumulation of lipids in PAP alveolar macrophages and in the GM-CSF KO model. We hypothesized that deficient PPAR γ results in the up-regulation of alveolar macrophage M-CSF, and excess M-CSF contributes ultimately to the accumulation of foam cells. We demonstrate herein that PPAR γ can regulate M-CSF production through transrepression of NF- κ B. Furthermore, because GM-CSF is required for alveolar macrophage PPAR γ expression, these data link the absence of GM-CSF with the accumulation of M-CSF in alveolar proteinosis.

Materials and Methods

Mice

Conditional PPAR γ KO mice—Homozygous floxed (+/+) PPAR γ mice were generously provided by Dr. F. J. Gonzalez (26). To achieve loss of PPAR γ in macrophages, homozygous floxed PPAR γ mice were crossed into a transgenic mouse containing the CRE gene under the control of the murine M lysozyme promoter (27). CRE-M lysozyme (+/+) mice were obtained from the Jackson Laboratory. Thus, control mice for these experiments consist of: floxed (+/+), CRE (–/–) mice (1) and floxed (–/–), CRE (+/+) mice (2).

²Abbreviations used in this paper: PPAR γ , peroxisome proliferator-activated receptor- γ ; BAL, bronchoalveolar lavage; ChIP, chromatin immunoprecipitation; KO, knockout; M-CSF, macrophage CSF; PAS, periodic acid-Schiff; PAP, pulmonary alveolar proteinosis; PPRe, peroxisome proliferator response element.

GM-CSF KO mice—This mouse strain was generated by G. Dranoff et al. (28). The mice have been backcrossed eight generations to C57BL/6. C57BL/6 wild-type mice obtained from The Jackson Laboratory were used as controls.

Murine cell source

Alveolar macrophages—Mice were injected subcutaneously with a lethal dose of ketamine (80 mg/kg) and xylazine (10 mg/kg). Bronchoalveolar lavage (BAL) was performed by inserting a cannula through a cut in the trachea into the bronchi and infusing 10 × 1-ml aliquots of warm PBS containing 0.2% lidocaine. The BAL fluid sample is recovered by aspirating the liquid with a syringe; we recovered 80 ± 23% of instilled fluid volume. Macrophages were harvested and cultured overnight before experimentation.

Resident peritoneal macrophages—Mice were injected with a lethal dose of ketamine and xylazine and cells recovered by lavage. Macrophages were harvested and cultured overnight before experimentation.

Bone marrow-derived macrophages—BALB/c mice were used for bone marrow-derived macrophage studies. The femur and tibia were removed and wiped with a sterile alcohol tissue (29,30). The bones were then put into RPMI containing antibiotics and, using a sterile 1 cc syringe, fresh RPMI was pushed through the bone marrow cavity. The bone marrow cells were counted with differentials and viability stains, followed by culture for 6–7 days with L929 support medium.

Lung pathology—Animal models and age-matched controls were euthanized; lungs were snap frozen for lipid stains.

Human BAL-derived macrophages

Alveolar macrophages were derived from BAL obtained by flexible bronchoscopy as previously described (31). Differential cell counts were obtained from cytopspins stained with a modified Wright's stain. All differential cell counts represented at least 200 cells. Mean viability of lavage cells was >95% by trypan blue dye exclusion.

Histological staining

Alveolar, bone marrow-derived, and peritoneal macrophages were isolated from 4 – 6-wk-old mice. Macrophages were stained with Oil-Red-O for neutral lipids (27,32). Alveolar macrophages from 6-wk GM-CSF KO were used as positive controls. Cells were fixed for 5 min in 1% paraformaldehyde in PBS. A stock solution of Oil-Red-O was diluted in methanol and filtered. Cells were incubated for 30 min in Oil-Red-O staining solution and then destained in 100% methanol for 5 min. The number of cells staining red in 10 high power fields (×40) was determined and expressed as percentage Oil-Red-O positive.

Cell culture conditions

Cells were cultured in 6-well, 12-well, or 24-well plates, depending on the experiment, at consistent cell densities. Primary cells were allowed to adjust to culture overnight before the addition of stimuli: LPS (50 –500 ng/ml), M-CSF (100 ng/ml), irreversible PPAR γ antagonist GW9662 (10 μ M; Sigma-Aldrich), and/or PPAR γ agonist pioglitazone (10 μ M, Takeda Chemical Industries). A proteasome inhibitor, 6-amino-4-(4-phenoxyphenylethylamino) quinazoline (Calbiochem), was used to block NF- κ B activation. Cells were harvested for either extracts for protein-DNA interactions, activated transcription factors, or mRNA analysis. Supernatants were harvested for secreted M-CSF.

Transfection experiments

PPAR γ expression vector was generously supplied by Todd Leff (Wayne State University). Two micrograms of CMV- β -gal (Jahar Haque, Cleveland Clinic Foundation) or pTR100 expression vector was transfected into 2×10^6 RAW 264.7 cells in a 6-well plate using calcium phosphate precipitation method as previously described (33). Transfection efficiency was verified with cotransfection with GFP expression vector (Invitrogen).

RNA purification and analysis

Bone marrow, peritoneal, and alveolar macrophages from GM-CSF and PPAR γ KO mice were cultured for 24 h in OptiMEM (Life Technologies/Invitrogen) before incubation with or without M-CSF stimulants (PMA, TNF), with concentration and duration being as prescribed by the initial experiment. Total RNA was extracted by RNeasy protocol (Qiagen). Expression of mRNA was determined by real time RT-PCR as previously described (7).

M-CSF protein

Murine and human ELISA assays were done according to manufacturers specifications (BioSource International).

Electrophoretic mobility shift assay

The assay was performed as previously described (34). In brief, RAW 264.7 cells were cultured with LPS (50 ng/ml) or pioglitazone (10 μ M) for 3 h. Supershifts were performed with anti-p65 and anti-p50 (Santa Cruz Biotechnology) added before the addition of the probe. The specificity of the probe was shown by incubating the extract with a 1000-fold molar excess of cold oligonucleotide. StormImager (Molecular Dynamics) and ImageQuant software were used for quantification of autoradiographs. The sequence of the NF- κ B binding site was 5'-AACTCCGGAATTTCCCTGGCCC-3'.

Chromatin immunoprecipitation (ChIP) assays

ChIP assays were performed following the instructions of the ChIP assay kit (Upstate Biotechnology) and the protocol outlined previously (29,35–38). Briefly, using the reagents provided in the chromatin precipitation kit, we immunoprecipitated protein-DNA complex Abs specific for PPAR γ (sc-7273, Santa Cruz Biotechnology), p65 (sc-8008), or p50 (sc-114) after bone marrow-derived macrophages were cultured in the presence and absence of pioglitazone (10 μ M), LPS (500 ng/ml), or GW9662 (5 μ M). Input DNA was normalized by OD (39). The presence of associated PPAR γ , p65, or c-Rel was measured by real-time PCR with the ABI Prism 7700 sequence detection system using SYBR Green PCR reagents (Applied Biosystems). PCR was done with nested primers to ensure specificity, and agarose gel analyses were performed after PCR amplification to ensure that a single product with expected size was amplified. The M-CSF promoter (40–44), peroxisome proliferator response element (PPRE), and NF- κ B primers are shown in Table I.

Statistical analysis

Analysis was performed using Prism GraphPad software version 3.0. Comparisons were performed using Student's *t* test or Mann-Whitney *U* test, as appropriate. For multiple comparisons, repeated measures ANOVA and Dunnett's test were used.

Results

Alveolar macrophage phenotype is similar in PPAR γ KO and GM-CSF KO mice

To determine the impact of the PPAR γ deficiency on PAP-like lung disease, we compared lung histopathology from 16-wk-old PPAR γ and GM-CSF KO mice after staining with PAS (Fig. 1). The GM-CSF KO mice were positive for PAS as previously reported (Fig. 1A) (15,28). Accumulated PAS-positive material was abundant in alveolar spaces in two out of seven PPAR γ KO mice, with one exhibiting robust intraalveolar PAS staining (Fig. 1B). PPAR γ KO mice at 6 wk did not have significant pathology (not shown). This suggests that intraalveolar accumulation occurs slowly as disease progresses. However, all PPAR γ KO mice had abundant PAS staining in the alveolar macrophages (Fig. 1B, *inset*). The BAL total and differential cell counts are displayed in Table II ($n = 5$ per condition). These data suggest that there are significantly more cells in the GM-CSF KO mice (mean \pm SD of $6.9 \pm 4.9 \times 10^4$ cells/ml) than in wild-type controls ($1.3 \pm 0.3 \times 10^4$ cells/ml, $p = 0.04$). There was a trend ($p = 0.07$) toward more cells in the PPAR γ KO mice as well ($2.9 \pm 1.7 \times 10^4$ cells/ml) vs the wild-type mice. Although macrophages were the most abundant cell type in all models, there were increased numbers of lymphocytes in both the GM-CSF KO and PPAR γ KO mice, and relative BAL neutrophilia as well in the PPAR γ KO mice. Observations in the GM-CSF KO mice are consistent with the literature (45).

Exogenous M-CSF is capable of inducing PAP-like surfactant uptake in alveolar macrophages

Because M-CSF has been associated with foam cell formation (46,47), and we previously observed elevations of M-CSF in the setting of GM-CSF deficiency (5), we hypothesized that M-CSF overproduction contributes to the lipid-cell phenotype observed in the PPAR γ and GM-CSF KO models. Alveolar macrophages from C57BL/6 mice were cultured in Lab-Tek chambers in the presence and absence of murine M-CSF (100 ng/ml) or human PAP surfactant material (200 ng/ml) (Fig. 2). The percentage of positive staining cells for each condition is depicted in Fig. 2E. Surfactant alone ($p = 0.001$) or M-CSF alone ($p = 0.008$) induced greater numbers of Oil-Red-O-positive alveolar macrophages than control cells. However, the combination of surfactant and M-CSF induced significantly greater uptake than either condition alone ($p = 0.03$ for the comparison of M-CSF alone or surfactant alone vs M-CSF + surfactant). Antibody-induced neutralization of M-CSF reversed the effects of exogenous M-CSF on lipid processing but did not alter the effects of surfactant alone on induction of Oil-Red-O-positive cells.

M-CSF is elevated in both the GM-CSF KO and macrophage-specific PPAR γ KO mice

We have previously reported that PPAR γ is deficient in human PAP (48). We have also shown that PPAR γ is deficient in the GM-CSF KO alveolar macrophages (49). To determine whether these two models also demonstrated similarities in M-CSF expression, we collected BAL cells and fluid from both KO genotypes. Gene expression was assessed using fresh whole cells, because most are alveolar macrophages (Table II). Fig. 3 demonstrates that both GM-CSF and PPAR γ KO mice have increased M-CSF gene expression and protein levels compared with controls ($n = 4-5$ for all conditions, $p \leq 0.002$ vs wild type mice). The elevation of M-CSF was specific for alveolar macrophages and the lung milieu because peritoneal macrophages did not express elevated levels of M-CSF mRNA or M-CSF protein in the peritoneal fluid compared with controls, regardless of whether the cells were elicited by thioglycollate or not (data not shown).

PPAR γ overexpression inhibits M-CSF production

RAW 264.7 cells were transfected with 2 μ g/ml PPAR γ expression vector. We measured the expression of M-CSF after 24 h with and without LPS stimulation. The transfection resulted in $10,809 \pm 1578\%$ increase in PPAR γ expression (Fig. 4, $p \leq 0.001$, $n = 3$). Expression of PPAR γ after transfection was not affected by the addition of LPS ($p = 0.98$). Constitutive expression of M-CSF in RAW cells was decreased to $31 \pm 4\%$ of control levels (CMV β -gal vector) by transfection with a PPAR γ expression vector. In the presence of LPS, M-CSF expression was induced by 20 ± 1.2 -fold vs control ($n = 3$, $p = 0.02$). LPS-induced M-CSF production was inhibited by overexpression of PPAR γ ($10.9 \pm 13.2\%$ of LPS alone, $p = 0.017$, $n = 3$). In additional experiments, RAW cells were cultured in the presence and absence of a specific PPAR γ agonist, pioglitazone, or an irreversible antagonist, GW9662. Pioglitazone repressed the expected induction of M-CSF transcription by $41 \pm 6\%$ percent (Fig. 5A, $p = 0.04$). Conversely, baseline RAW cells treated with GW9662 spontaneously increased their M-CSF gene expression by $532 \pm 241\%$ (Fig. 5B, $p = 0.02$), suggesting that basal PPAR γ activity maintains repression of the M-CSF promoter, even in the absence of inflammatory stimuli. To assess the generalizability of these findings, we repeated the experiments using bone marrow-derived macrophages. LPS stimulated bone marrow-derived macrophages ($n = 4$) had a 21 ± 0.5 -fold increase in M-CSF mRNA gene expression, which was decreased to 2.2 ± 0.1 ($p = 0.001$) with pioglitazone. Treatment of the bone marrow macrophages with GW9662 resulted in a 57 ± 1.7 -fold increase in M-CSF mRNA expression ($p \leq 0.001$). Because previous studies have shown that alveolar macrophages from PAP patients express high levels of M-CSF (17), healthy control alveolar macrophages were cultured in the presence and absence of either pioglitazone or PPAR γ agonists/antagonists to determine whether the impact of PPAR γ agonists/antagonists would be the same on M-CSF production. Similar to the RAW cells and the bone marrow-derived macrophages, healthy control alveolar macrophages treated with GW9662 secreted $12 \pm 2\%$ more M-CSF than did cultured controls ($p = 0.04$). LPS-stimulated alveolar macrophage M-CSF production was decreased by $30 \pm 12\%$ with the addition of pioglitazone ($n = 3$, $p = 0.02$). The observed modest change in M-CSF protein production compared with mRNA expression may be due to the release of preformed M-CSF, enhanced M-CSF stability relative to M-CSF protein, and/or preferential production of membrane-bound M-CSF. This is the subject of ongoing studies.

PPAR γ regulates M-CSF through NF- κ B

Analysis of the M-CSF promoter, as well as prior reports, suggested that NF- κ B is crucial for constitutive and inducible gene expression (50). To determine whether PPAR γ binding to the NF- κ B site affected M-CSF transcription, experiments were designed to measure M-CSF transcription in the presence and absence of a proteasome inhibitor, 6-amino-4-(4-phenoxyphenylethylamino) quinazoline, which prevents activation of NF- κ B by blocking I κ B α degradation. RAW 264.7 cells were stimulated for 6 h with LPS, resulting in 21.6 ± 0.9 -fold increase in M-CSF expression (Fig. 6, $n = 4$ for each condition). LPS-induced M-CSF expression was reduced by $60 \pm 26\%$ when NF- κ B activation was inhibited. Pioglitazone treatment also decreased LPS-stimulated M-CSF expression, by $68 \pm 15\%$ compared with the LPS control ($p < 0.05$). The combination of both pioglitazone and NF- κ B inhibition resulted in a further reduction of M-CSF expression, to $19.7 \pm 25\%$ of LPS alone ($p < 0.001$ vs LPS). These data suggest that PPAR γ regulates M-CSF production through repression of NF- κ B. PPAR γ regulation of M-CSF did not appear to involve MAPK pathways because ERK inhibitor (PD 98059) and p38 inhibitor (SB 203580) did not alter M-CSF gene expression (data not shown).

Pioglitazone inhibits NF- κ B activation

Pioglitazone, a PPAR γ agonist, has previously been shown to decrease activity of NF- κ B-regulated gene promoters in transient transfection assays (51). To confirm that this effect is mediated by inhibition of NF- κ B binding to DNA, we performed EMSAs using RAW 264.7 cells cultured for 3 h in the presence of LPS, pioglitazone, or pretreated with pioglitazone for 30 min before the addition of LPS. The extent of NF- κ B DNA binding was quantified by measuring radioactivity with phosphorimaging. Constitutive NF- κ B binding was low and was not significantly affected by pioglitazone alone (Fig. 7). After pretreatment with pioglitazone, LPS-induced formation of NF- κ B-DNA-binding complexes was reduced by $30.6 \pm 6.9\%$ ($n = 4$, $p < 0.01$ by Tukey's test).

PPAR γ binds to NF- κ B site and PPRE site upstream of the M-CSF promoter

To assess whether PPAR γ could inhibit NF- κ B transactivation of the M-CSF promoter, we used bone marrow-derived macrophages for ChIP experiments. BALB/c bone marrow cells were differentiated into macrophages using L929-supplemented medium. Cells were harvested and cultured for 7 days before experiments. Bone marrow-derived macrophages were then treated with LPS (500 ng/ml) or pioglitazone (10 μ M). Cell lysates were immunoprecipitated with anti-PPAR γ , anti-p65, and anti c-Rel. Binding to the M-CSF promoter was determined by real-time PCR. Positive MCSF promoter PCR reactions in the different immunoprecipitated reactions reflect transcription factor association with the M-CSF promoter. As expected, LPS resulted in p65 and c-Rel association with the NF- κ B site (Fig. 8B). Activation of PPAR γ by pioglitazone enhanced PPAR γ association with the same region (Fig. 8A, $n = 2$), while LPS nearly abrogated PPAR γ binding to the promoter. These data suggest that activation of PPAR γ is capable of repressing inflammatory signaling that can activate transcription at the M-CSF promoter. The impact of PPAR γ association with a PPRE site in the M-CSF promoter is unknown at this time (Fig. 8C).

Discussion

GM-CSF is essential for alveolar macrophage differentiation and surfactant catabolism (7). The mechanism whereby deficiency of bioactive GM-CSF induces accumulation of surfactant material in human PAP and the GM-CSF KO model has not been delineated to date. Our data suggest that the effect of GM-CSF deficiency to enhance M-CSF expression may be an important clue about its role. The dysregulation of M-CSF appears to be due to deficiency of PPAR γ and is capable in vitro of inducing lipid accumulation in alveolar macrophages. In support of this general concept, both the macrophage-specific PPAR γ KO mouse and the GM-CSF KO mouse have similar accumulation of PAS-positive lipid material in the intraalveolar space and alveolar macrophages. Cells harvested from the peritoneum did not demonstrate this morphology, suggesting a mechanism unique to the alveolar microenvironment.

Additionally, the data presented herein demonstrate that M-CSF production in alveolar macrophages can be regulated by PPAR γ . Using chromatin immunoprecipitation, PPAR γ expression vectors and inhibitors for NF- κ B, ERK, and JNK, we provide evidence that PPAR γ regulates M-CSF through transrepression of NF- κ B activity. It is possible that the effects of pioglitazone and the NF- κ B inhibition involve unique or independent mechanisms. The present report does not fully resolve this issue. We think it is likely, however, that the repressive effect of PPAR γ activation is mediated by blockade of NF- κ B association with the promoter. Data in support of this hypothesis include the EMSA analysis and the very robust association of PPAR γ with the NF- κ B response element. The magnitude of reduction of NF κ B binding in the EMSA is almost identical to previously reported effects of pioglitazone on LPS induction of NF κ B-luciferase in RAW cells (51). Taken together, these results suggest that the effects of pioglitazone are mediated by prevention of NF κ B transactivation of the

promoter. This mechanism is congruent with the model proposed for regulation of NF- κ B induction of the murine iNOS promoter in RAW cells (52–55).

Normally, production of M-CSF is low, a phenomenon that is partly due to basal repression of the M-CSF promoter by PPAR γ . In the presence of inflammatory signaling via NF- κ B, up-regulated M-CSF promoter activity can be modulated by PPAR γ . These observations are consistent with the PPAR γ corepression mechanism suggested by Pascual et al. (52). From these observations, we propose the model depicted in Fig. 9, showing that in the absence of activation a corepressor complex may block M-CSF promoter activity. When PPAR γ is activated it binds to and stabilizes the corepressor, preventing accumulation of coactivator proteins and NF- κ B transactivation of the promoter, which requires degradation of the corepressor complex. In the absence of PPAR γ , constitutively low-level NF- κ B binding at the promoter allows basal MCSF production.

M-CSF is a CSF associated with the maturation, differentiation and survival of monocyte/macrophages (10,41). During early myeloid differentiation, M-CSF alone cannot support the proliferation and differentiation of multipotent progenitor cells; however, it synergizes with other growth factors such as stem cell factor (also known as kit ligand) and IL-3 to produce mononuclear phagocyte progenitor cells (56). After this initial differentiation process, MCSF itself can regulate the proliferation and differentiation of mononuclear phagocyte progenitor cells to monocytes and macrophages in addition to the survival, proliferation, and function of fully differentiated macrophages. Additionally, M-CSF synergizes with receptor activator of NF- κ B ligand (RANKL) to regulate the differentiation of mononuclear phagocytes to osteoclasts. Studies have shown that M-CSF induced bone-resorbing osteoclasts can be inhibited by PPAR γ ligands (57), which are congruent with our observations associating M-CSF repression with PPAR γ activation.

Overabundance of M-CSF can also lead to the development of disease. M-CSF-associated enhancement of atherosclerosis is thought to be mediated by a local production of M-CSF leading to the accumulation of cholesterol-filled foam cells in atherosclerotic plaques (56). In obesity, the ratio of M-CSF-dependent macrophages to adipocytes in adipose tissue is positively correlated with both adipocyte size and body mass (23). These and other studies suggest that macrophages have an active role in morbid obesity and that macrophage-based inflammatory activity supported by locally produced M-CSF might contribute to the pathogenesis of obesity-induced insulin resistance (58). M-CSF also has a role in some inflammatory diseases. The administration of Abs to M-CSF in the collagen-induced arthritis model results in reduced severity of arthritis in mice, and M-CSF-deficient mice show a decrease in recruitment, proliferation, and activation of macrophages in models of inflammation (58,59). Our data suggest therefore that PPAR γ has the potential to alter monocyte/macrophage activation through the regulation of M-CSF, independent of GM-CSF. This mechanism explains the observation that there is constitutive hyperproduction of M-CSF in the GM-CSF KO mouse, because PPAR γ is markedly deficient.

GM-CSF is essential for alveolar macrophage differentiation, surfactant catabolism, and PPAR γ expression (14,31,48,60). One of the implications of loss of GM-CSF-induced PPAR γ expression is on the production of M-CSF. These studies are the first to directly link PPAR γ to M-CSF production. M-CSF is essential in the survival, proliferation, and activation of monocyte/macrophages. The PPAR γ KO expresses normal levels of GM-CSF mRNA, but also has elevated levels of M-CSF. This suggests that in any scenario in which PPAR γ becomes deficient or significantly decreased such as in inflammation, a switch turns on in which macrophages may become alternatively activated potentially through the production of M-CSF. The nature and phenotype of alveolar macrophage activation ultimately defines the adaptive and innate immunity of the response to the insulting stimulus. These studies therefore

are the first to directly associate PPAR γ to alveolar macrophage M-CSF production and potential activation and regulation of pulmonary immunity.

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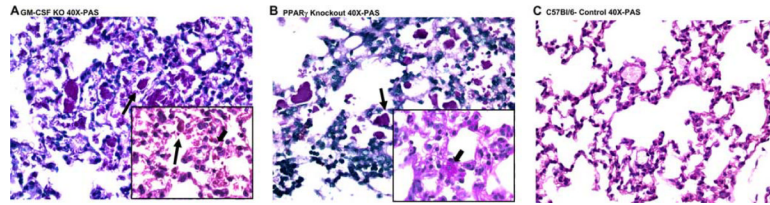
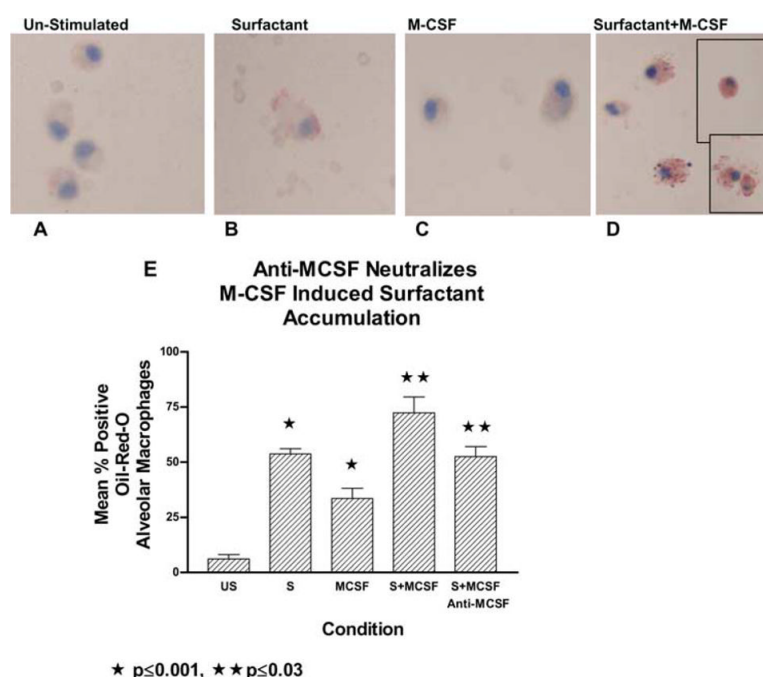


FIGURE 1.

PPAR γ knockout alveolar macrophage Pathology resembles the GM-CSF KO model. GM-CSF KO (A), PPAR γ KO (B), and C57BL/6 control (C) mice were sacrificed, and the lungs stained with periodic-acid Schiff ($\times 40$). The GM-CSF KO model demonstrates scattered foci of intraalveolar PAS-positive material (thick arrows, A) and lipid-engorged alveolar macrophages (thick arrow, $\times 100$ inset). All of the PPAR γ KO mice (7 of 7 mice) exhibited similar PAS-positive material in alveolar macrophages (B, $\times 100$ inset). Similar to the GM-CSF KO animals, several of these mice (2 of 7) also developed intraalveolar PAS-positive material (B, thin arrow).

**FIGURE 2.**

M-CSF induces alveolar macrophages to take up surfactant. Alveolar macrophages were obtained from C57BL/6 mice and cultured in vitro with 200 ng/ml surfactant obtained from a PAP patient in the presence and absence of human recombinant M-CSF. Figures depict $\times 40$ images, representative of six independent experiments. Both surfactant ($p = 0.001$ vs controls) and M-CSF ($p = 0.008$) induced Oil-Red-O-positive cells. Alveolar macrophages incubated with surfactant and M-CSF had a cumulatively greater uptake of Oil-Red-O staining lipids compared with either condition alone ($p = 0.03$ vs either). Each condition was evaluated for (and counted in 6 frames of at least 200 cells) by blinded numerical designation. Data represent mean percentage of positive Oil-Red-O staining \pm SEM ($n = 6$). Abs to M-CSF neutralized the effect of M-CSF on surfactant uptake to levels comparable to surfactant alone. US, Unstimulated; S, surfactant.

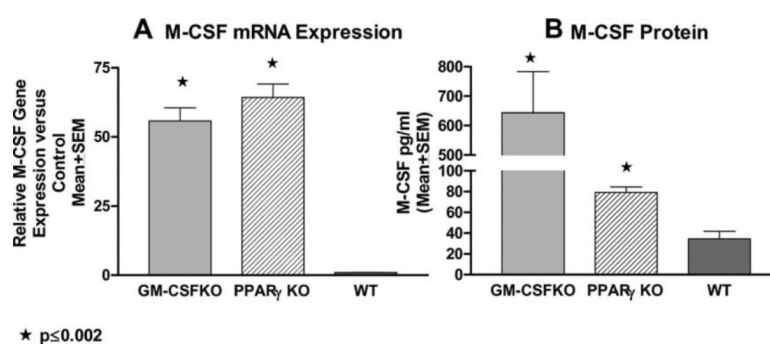


FIGURE 3.

M-CSF gene expression and protein are elevated in BAL specimens from GM-CSF and PPAR γ KO mice. Acellular BAL fluid was assessed for M-CSF protein by ELISA, and BAL cell pellets were evaluated for M-CSF mRNA. Compared with wild-type mice ($n = 5$), BAL cells from both GMCSF KO ($n = 4$) and PPAR γ KO ($n = 4$) mice demonstrated increased M-CSF gene expression ($p \leq 0.002$ for each comparison, *B*). Similarly, BAL protein levels were increased in both models when compared with wild-type mice (*B*, $p < 0.002$, $n = 4$ per condition).

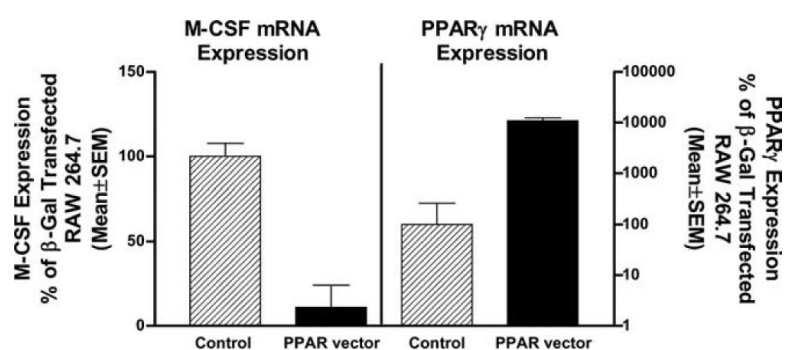
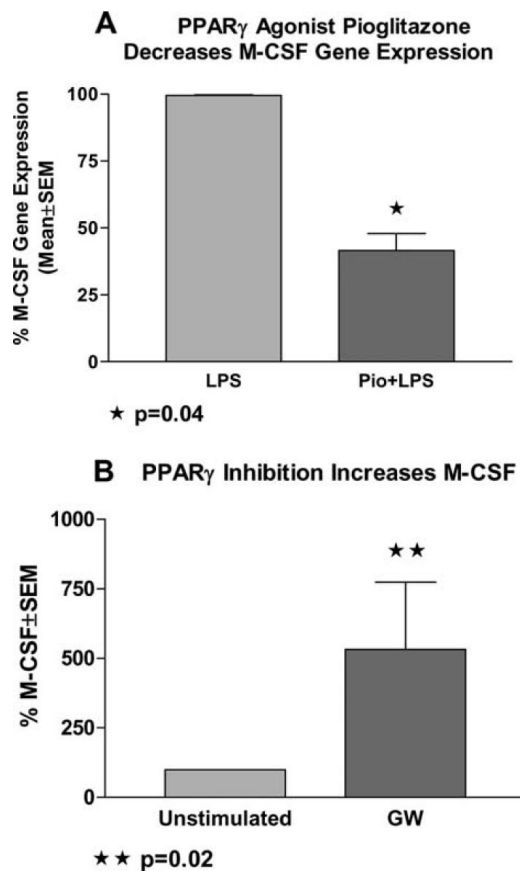


FIGURE 4.

Transfection of PPAR γ expression vector into RAW 264.7 cells attenuates LPS-mediated induction of M-CSF. RAW 264.7 cells were transfected with 1 μ g PPAR γ murine expression vector. We measured the expression of M-CSF after 24 h in the presence and absence of LPS. Transient transfection of the PPAR γ expression vector resulted in $10,809 \pm 1,578\%$ (mean \pm SEM) increased expression of PPAR γ mRNA expression compared with the control (β -gal) vector (right bars, $n = 3$, $p \leq 0.001$). Compared with transfected controls (β -gal), LPS-induced M-CSF production was inhibited by $90.1 \pm 13.2\%$ with the overexpression of PPAR γ expression vector (left bars, $p = 0.017$, $n = 3$).

**FIGURE 5.**

M-CSF secretion is enhanced by PPAR γ antagonists and suppressed by PPAR γ agonist. RAW cells were cultured in the presence and absence of pioglitazone or GW9662 at baseline or after stimulation with LPS. LPS-stimulated RAW cells treated with pioglitazone expressed $41 \pm 6\%$ significantly less M-CSF mRNA (A, $p = 0.04$, $n = 4$) and $12 \pm 0.7\%$ less M-CSF protein ($p = 0.01$) compared with the LPS cultures alone. Conversely, baseline RAW cells treated with GW9662 increased their M-CSF gene expression and protein by $532 \pm 242\%$ (B, $p = 0.02$, $n = 3$) and $11.2 \pm 1\%$ ($p = 0.03$), respectively.

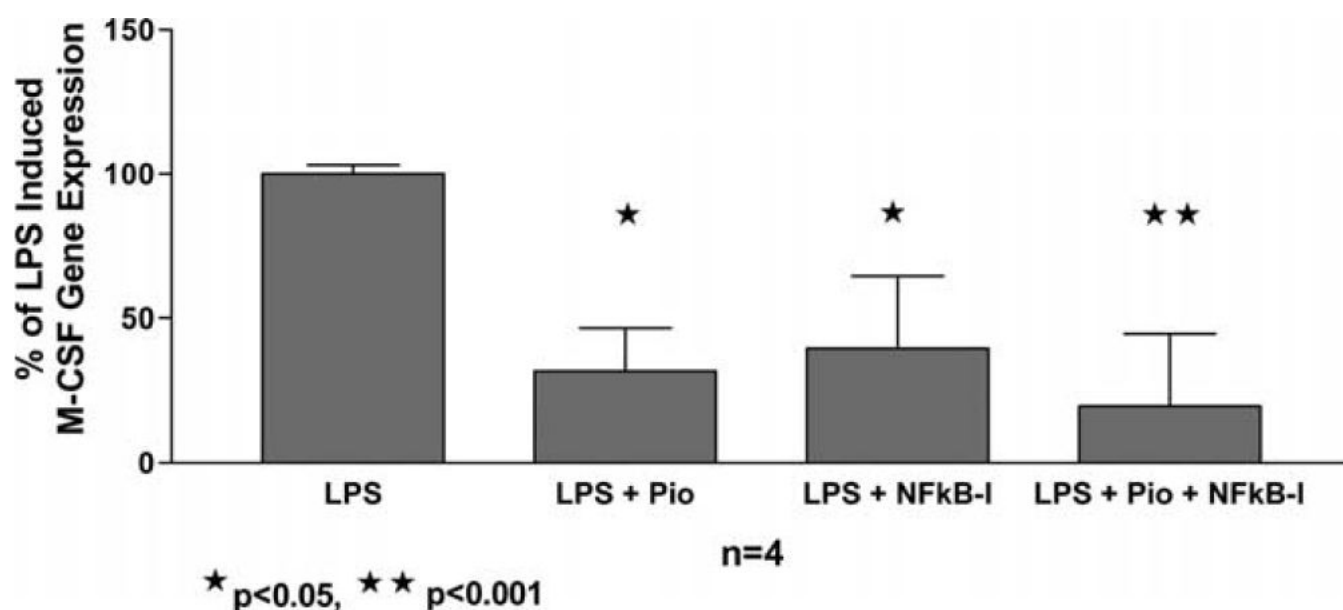


FIGURE 6.

PPAR γ regulates M-CSF through NF- κ B. RAW 264.7 cells were stimulated with LPS, which resulted in a 21.6 ± 0.9 -fold increase in M-CSF expression. LPS induced M-CSF expression was reduced by $60 \pm 26\%$ when the NF- κ B was inhibited with the proteasomal blocker. Pioglitazone treatment also decreased LPS-stimulated M-CSF expression, by $68 \pm 15\%$ of the LPS control ($p < 0.05$ vs LPS alone). The combination of both pioglitazone and NF- κ B inhibition resulted in $80 \pm 25\%$ reduction of M-CSF expression ($p < 0.001$ vs LPS). These data suggest that PPAR γ can regulate M-CSF induction through repression of NF- κ B.

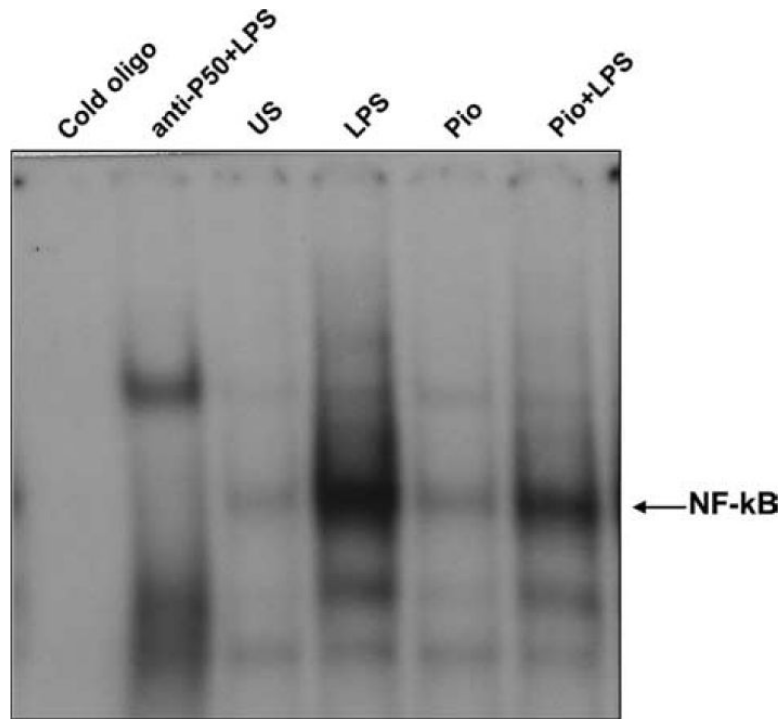
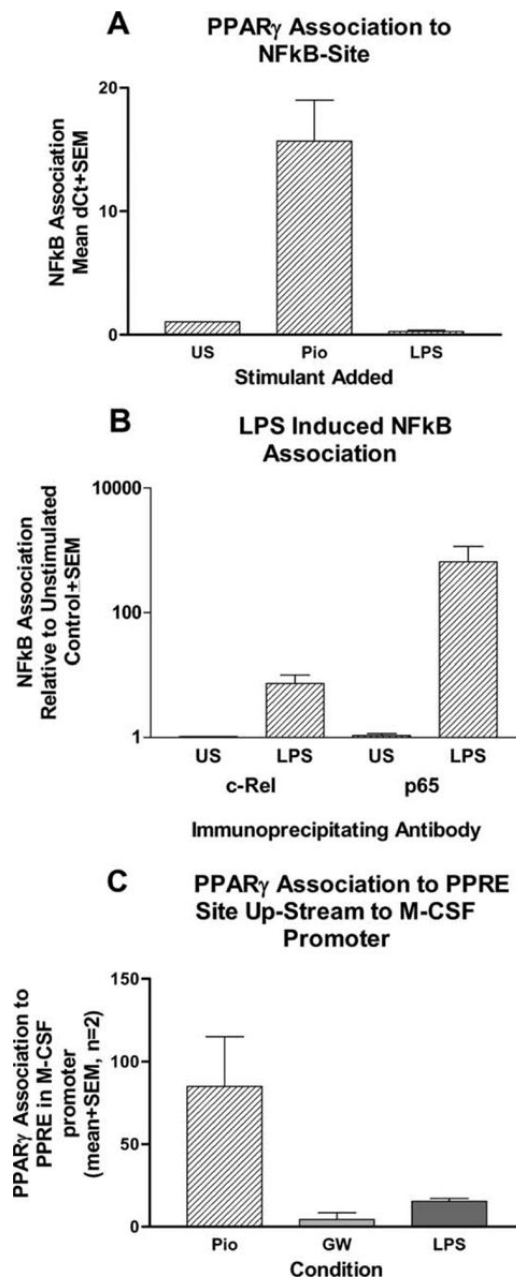
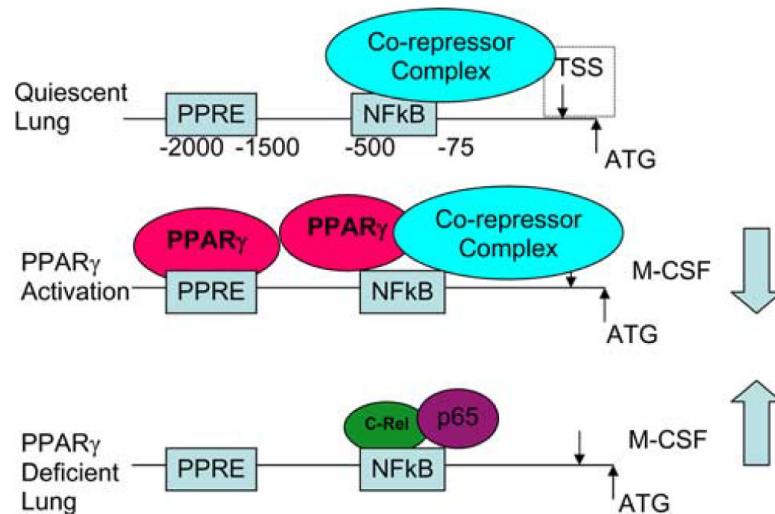


FIGURE 7.

Pioglitazone inhibits LPS-mediated NF-κB activation. Whole-cell extracts were analyzed by EMSA using a ^{32}P -labeled oligonucleotide containing the κB consensus sequences and analyzed on a 4% nondenaturing acrylamide gel. Specificity of the band was confirmed by supershift analysis with p50 and p65 Abs and competition with cold oligonucleotide. Representative image from four independent experiments is shown. Quantification using the StormImager with ImageQuant analysis revealed that pretreatment with pioglitazone before addition of LPS decreased NF-κB binding by $30.6 \pm 6.9\%$ (mean (SEM), $p < 0.01$ by Tukey's test). US, Unstimulated; Pio, pioglitazone.

**FIGURE 8.**

PPAR γ inhibits LPS-induced NF- κ B association with the M-CSF promoter. ChIP was performed using BALB/c bone marrow-derived macrophages. After treatment with LPS (2 μ g/ml), pioglitazone (Pio, 10 μ g/ml), or GW9662 (GW, 10 mM), cell lysates were subjected to immunoprecipitation with anti-PPAR γ , anti-c-Rel, or anti-p65. Binding to the M-CSF promoter was determined by real-time PCR. LPS stimulation resulted in c-Rel and p65 binding to the NF- κ B site upstream of the M-CSF promoter (B). Activation of PPAR γ by pioglitazone increased PPAR γ association with the NF- κ B response element, which was nearly eliminated with NF- κ B activation by LPS (A). Pioglitazone also resulted in PPAR γ binding to the M-CSF PPRE promoter region (C).

**FIGURE 9.**

Model of PPAR γ regulation of M-CSF transcription. Data from the ChIP and culture studies were put together to develop a model of a working hypothesis in which PPAR γ regulates M-CSF through NF- κ B. PPAR γ inhibits association of NF- κ B proteins with the promoter, an effect that is enhanced in the presence of PPAR γ activation. In the presence of NF- κ B activation, PPAR γ binding to the promoter is down-regulated unless PPAR γ is ligand-activated by pioglitazone. In the absence of PPAR γ , there is a potential constitutive production of M-CSF through p65/c-Rel binding to NF- κ B transcription site.

Table I

Primers for TaqMan of M-CSF promoter

Murine M-CSF Promoter	
mCSF-PPRE-F	5'-gtgaagtgaatggggtgct-3'
mCSF-PPRE-R	5'-gtgattacgtttagaaccactgaa-3'
mCSF-NFκB-300F	5'-tccccattcaagtcctgttc-3'
mCSF-NFκB-300R	5'-tgtgcagcctcctcaaagta-3'
mCSF-NFκB-50F	5'-gggcctctggggtgtagtat-3'
mCSF-NFκB-50R	5'-ccgaggcaacttcacttt-3'

Table II

Cell counts in BAL

Model	Total Cell Count ($\times 10^4$)	Alveolar Macrophages (%)	Lymphocytes (%)	Neutrophils (%)
Wild type	1.34 ± 0.30	98 ± 9	2 ± 1.5	1 ± 1
GM-CSF KO	6.86 ± 4.93	70 ± 6	24 ± 3	5 ± 3
PPAR γ	2.92 ± 1.67	72 ± 9	13 ± 2	13 ± 4